AD-A094 144 NAVAL RESEARCH LAB WASHINGTON DC F/G 20/8

STORAGE-RING GENERATION OF HIGH-ENERGY NEUTRINO BEAMS.(U)

DEC 80 F J KELLY, A W SAENZ, H UEBERALL

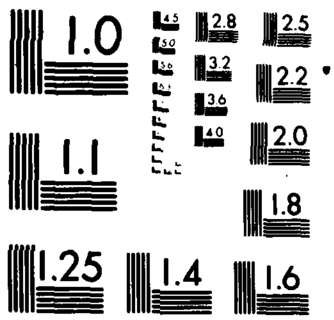
UNCLASSIFIED NRL-8457 NL

END

DATE FILMED

2 81

DTIC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

AD A094144

FILE COPY

December 31, 19

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) NRL ~~Report~~ 8457	2. GOVT ACCESSION NO. AD-A094 144	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) STORAGE-RING GENERATION OF HIGH-ENERGY NEUTRINO BEAMS,		5. TYPE OF REPORT & PERIOD COVERED (9) Interim report, on a continuing NRL Problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Francis J. Kelly, A. W. Saenz, ~~and~~ H. Uberall	(11) 31 Dec 80	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375	(12) 16	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N RR0120241 66-0405-0-0
11. CONTROLLING OFFICE NAME AND ADDRESS (16) RR01202		12. REPORT DATE December 31, 1980
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (17) RR0120241		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Neutrino telecommunications
Neutrino oscillations
Neutrino beam production
Monochromatic neutrinos
Storage rings

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The storage ring method of generating high-energy neutrino beams provides a source of monoenergetic neutrinos, which can be used for transterrestrial neutrino oscillation studies and for neutral-current neutrino experiments in the laboratory. In this report, we consider several possible storage ring configurations, and estimate their counting rates for scientific and communications applications.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

251 950

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

STORAGE-RING GENERATION OF HIGH-ENERGY NEUTRINO BEAMS

INTRODUCTION

The present study was primarily motivated by the authors' interest in the use of high-energy neutrino beams for global communication. We have shown the scientific feasibility of this idea in earlier publications [1-4], where our analysis was based on the conventional method of generating neutrino beams at high-energy accelerators, *i.e.*, by employing decay tunnels.

In this report, we discuss four other methods for producing high-energy neutrino beams. These methods are based on high-energy pion or muon decay in specially shaped storage rings, the main decays of interest in the present connection being

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \tag{1a}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \tag{1b}$$

which produce beams of muon neutrinos and antineutrinos, *i.e.*, the neutrinos of principal interest for communication purposes.

In a sense, such a storage ring constitutes a decay tunnel which is bent around and closed upon itself, and which provides, in effect, an infinitely long decay path, thus allowing the decay of all pions (or muons) stored in it.

The obvious drawback of storage rings is that they have a rather limited range of momentum and solid-angle beam acceptance, which cuts down on the neutrino intensities. Nevertheless, neutrino beams generated by the pion decay Reaction (1a) in specially designed storage rings could be advantageous for telecommunication purposes. Furthermore, pion storage rings would yield neutrino beams that are essentially monoenergetic in any given direction. Such monochromatic muon neutrino beams are not available at present, and are of interest in several areas of neutrino physics. In particular, they would constitute a unique tool for investigations of neutrino oscillation phenomena in neutrino beams transmitted over great distances through the earth. This is a subject highly relevant to neutrino communication over global distances.

The organization of this report is as follows. In the second section, we discuss the generation of neutrino beams in storage rings. The third section is devoted to a discussion of muon event rates induced by such beams at great distances from the source, and it also considers the applicability of neutrino beams from pion storage rings to telecommunication. Scientific applications of pion storage rings are mentioned in the fourth section. The fifth section summarizes our conclusions.

Manuscript submitted September 4, 1980.

NEUTRINO BEAM PRODUCTION BY STORAGE RINGS

The following storage-ring methods of neutrino-beam generation will be considered:

(a) High-energy accelerators such as the 400 GeV Fermilab accelerator or its soon-to-be available upgraded 1 TeV version, the Tevatron [5] would be used as pion sources. A momentum byte of π^+'s (whose energy spectrum for the appropriate operating mode has average energy ~150 GeV at Fermilab and could reach an average energy ~350 GeV at the Tevatron [6]) would be injected into a storage ring, where the pions would decay into ν_μ's according to Reaction (1a).

(b) Such accelerators could be used as muon sources. An external μ^+ beam at one of these accelerators or a suitable momentum byte thereof would be injected into a storage ring, decaying therein mainly by Reaction (1b), and thereby yielding $\bar{\nu}_\mu$'s and ν_e's. (The present external μ^+ beam at Fermilab has energy ~200 GeV; the corresponding beam at the Tevatron could have an energy of up to ~800 GeV [7].)

(c) An existing meson factory (such as LAMPF or SIN) would be used as a low-momentum (~100 MeV/c) μ^+ source. These muons would be injected into a linear or racetrack-type accelerator, accelerated to ~200 GeV or more, and then injected into a storage ring, where they would furnish a $\bar{\nu}_\mu$ beam.

(d) An electron accelerator would be used as a muon beam source. The muons are accelerated as in (c), and injected into the storage ring.

Before discussing the relative merits of these schemes, and the neutrino event rates to be achieved by their use, we will first describe the pertinent storage rings and how they could provide a directional neutrino source.

Any straight segment of a circulatory π^+ or μ^+ storage ring is a generator of a directional neutrino beam *via* the appropriate decay, Reaction (1). Thus, we simply have to point a straight segment of the machine into a desired direction of neutrino propagation. With respect to a given direction, the optimal efficiency of such a ring is 50%, but in practice it will be ~25% or below if the curved portions of the ring are comparable in length to the straight sections. Note, *e.g.*, that for a ring shaped like an elongated twisted doughnut, the neutrinos from both straight sections travel downward beneath the earth's surface and could provide beams for two long-distance communication experiments in different directions.

In theory, a variable-direction neutrino beam can be achieved in this way also. Consider a muon storage ring having straight and curved segments, with elongated straight segments of the storage ring relative to the curved portion. To change the direction of pointing the beam, one must change the direction of the straight track portion of the device. At the same time, the curved portion of the device can remain fixed as shown in Fig. 1 in which four variable strength magnets (each able to bend the beam through an angle $\Delta\theta$) are used to produce a change of direction of the beam. In Fig. 1 the curved portion of the storage ring remains fixed in space (or in the ground). The only movable parts are the $\Delta\theta$ angle-changing magnets and the vacuum pipes that provide a drift space for the pions or muons between the magnets. These parts are moved to provide a modification of the angle at which the straight beam arm is to point. The efficiency of this device is just d/S, where d is the length of the straight beam arm, and S is the length of the total track circumference. The neutrinos emitted from the straight segment called ARM 2 are wasted, only the neutrinos from ARM 1 go down to a desired receiver.

Several variations on this principle are possible. A set of straight-section vacuum pipes located in a biconical vault underground can be arranged to point into a set of directions, and can be used to pro-

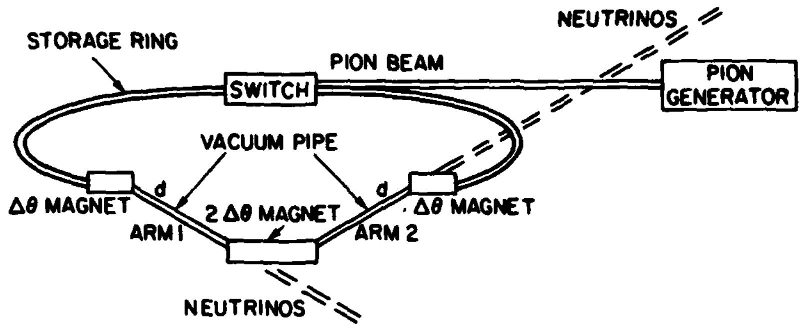


Fig. 1 — Neutrino beam generator for mobile receivers, permitting pion track variation

duce the neutrino beam one at a time, or several at a time if the pion or muon beam intensity is sufficient. Or, a corrugated storage ring can be constructed that possesses several straight sections pointing into different directions, which would all produce a neutrino beam simultaneously. Figure 2 shows a storage ring with three straight sections, and the resulting neutrino beams.

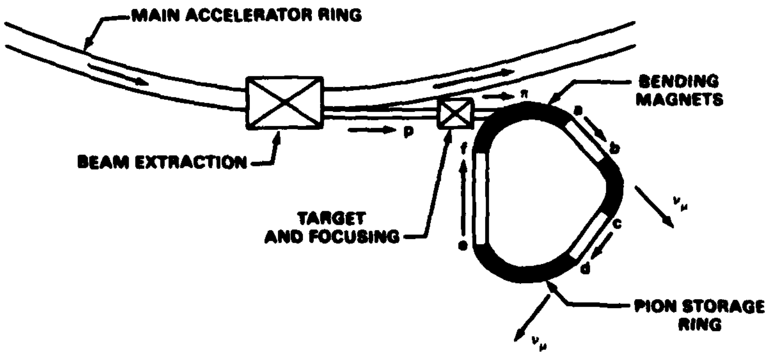


Fig. 2 — Generation of several neutrino beams from a pion storage ring with multiple straight sections

As is well known, the dimensions of the storage rings of interest here are determined by the pion or muon momenta, and by the type and quality of the available bending magnets. The magnetic rigidity of a relativistic charged particle is proportional to its energy. Thus, using the Tevatron dimensions as a guide, a reasonable assumption on the size of a high-energy storage ring is that its radius in meters should be the same as the energy of the desired stored particle in GeV. For the applications envisioned here, this means that the needed storage rings would have curved sections with radii between ~100 m and ~400 m. The lengths of the straight sections are determined by a tradeoff between the neutrino production efficiency $\eta = d/S$ (large arm lengths d being desirable) and the constraints of keeping the dimensions of the ring small for reasons of practicality. Consider, for example, a ring for storing 100 GeV pions. If one takes the ring to have the shape of an elongated doughnut, with two end-circles of 100 m radius, then $\eta \sim 20\%$ for $d = 200$ m.

EVENT RATES INDUCED AT LARGE DISTANCES BY NEUTRINO BEAMS FROM STORAGE RINGS—APPLICATION TO NEUTRINO COMMUNICATION

In this section, we discuss the muon production rates induced at large distances by neutrino beams obtained by methods (a) through (d), the produced muons constituting the signature of the beams. In a previous paper [3], it was found that a neutrino beam from an accelerator of the Fermilab type (with a 400-m decay tunnel) would produce, by the combined reactions

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}, \tag{2a}$$

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}, \tag{2b}$$

about 3.8×10^3 muons/h in a water detector of mass $M = 10^8$ tons situated at a distance $R = 3.2 \times 10^3$ km from the accelerator, assuming a proton intensity of 5×10^{13}/pulse and 450 pulses/h. It was also assumed in Ref. 3 that the focusing of the pions and kaons produced by the primary protons was "good," but not perfect, meaning that the muon-production rates were assumed to be $\sim 1/3$ of the rates for perfect focusing. For the Tevatron (equipped with a 1-km decay tunnel), we predicted a muon rate of 5.8×10^3/h in a water detector of $M = 10^7$ tons at $R = 10^4$ km, under the same assumptions. These rates would be sufficient for low-data-rate neutrino communications (of about 3 bits/s) and more than enough for scientific experiments designed to study neutrino transmission through the earth.

The next subsection is devoted to a discussion of method (a), and the following subsection considers methods (b) through (d).

Method (a)

The muon rates mentioned in the first paragraph of this section were predicted [3] by using the Wang model of pion production [8] and a crude modification thereof for kaon production [9]. The simpler (but *probably less accurate*) Stefanski-White model of pion production [10] will be used in the present subsection. It predicts muon rates which are lower by $\sim 1/2$ than those obtained by means of the Wang model. Nevertheless, the Stefanski-White model is accurate enough for our purposes, and it has the virtue of allowing one to arrive at simple analytical expressions for the relevant rates.

We shall compare muon production rates caused in distant detectors by ν_μ beams produced by π^+ decay in storage rings and conventional decay tunnels. Let a momentum byte Δp of the π^+ spectrum generated by an accelerator-proton beam incident on a suitable target be injected into a storage ring having a straight section which is "aimed" at a distant Cerenkov water detector. Let R_1 denote the μ^- event rate in the detector due to Reaction (2a), which is induced by the ν_μ beam generated by the decay of the pions in the straight section. By definition, R_1 pertains to the case when *unfocused* pions are injected into the ring. We define R_1' in the same way as R_1, except that in the case of R_1' we assume that the byte Δp of pions is *perfectly focused* before injection, so that the entire byte is admitted into the ring. Now suppose that the π^+'s produced by the primary protons are *perfectly focused* and are then transported into a straight decay tunnel which is directed toward the detector. Let R_2 be the μ^- event rate occurring in the detector *via* Reaction (2a), induced by the ν_μ beam emerging from the decay tunnel.

In computing R_1, R_1', and R_2, we have made several simplifying assumptions, stated in more detail in the appendix. We assumed that decaying pions in the straight section of the considered storage ring and in the decay tunnel have been so well focused that the transverse orbital oscillations of the pertinent pion beams can be neglected. We also supposed that the decay tunnel and the straight section of the ring points accurately toward the detector, which subtends such a small angle that all the neutrinos reaching it proceed from forward or near-forward pion decay.

Table 1 gives values of R_1 and R_1', per pulse of 5×10^{13} protons, as a function of $z = cp/E_0$, where c is the speed of light and p is the pion momentum at which a byte Δp is taken. These values were obtained by means of Eq. (A6) of the appendix and the modification of Eq. (A6) appropriate to R_1'. The values of R_1 and R_1' in Table 1 correspond to a target whose length l in units of the proton-nucleus absorptive interaction length is unity (maximally efficient target), to the values $M = 10^6$ tons and $D = 10^3$ km of the water mass M of the detector and the distance D between the accelerator and the detector, and to $\Delta p/p = 0.01$ and $\eta = 0.2$. As far as the values of R_1 are concerned, the remaining relevant parameters were chosen in two ways:

(i) $E_0 = 0.4$ TeV, $\Delta\Omega = 15\ \mu$sr,

(ii) $E_0 = 1.0$ TeV, $\Delta\Omega = 15\ \mu$sr,

where $\Delta\Omega$ is the solid angle of storage-ring acceptance. In the case of R_1', the remaining parameter, E_0 was chosen as follows:

(i)′ $E_0 = 0.4$ TeV,

(ii)′ $E_0 = 1.0$ TeV.

Table 1 can be readily extended to other values of the parameters. Indeed, notice that for the large D's and small $\Delta p/p$'s for which Eq. (A6) and its alluded modification hold, one has $R_1 \propto \eta M D^{-2}(\Delta p/p)$ and $R_1' \propto \eta M D^{-2} E_0^3 (\Delta p/p)$.

Table 1 — Values of R_1 and R_1' *vs* z per pulse of 5×10^{13} protons incident on an $l = 1$ target, for $M = 10^6$ tons and $D = 10^3$ km. Cases (i) and (ii) are considered for R_1, and cases (i)′ and (ii)′ for R_1'.

z	R_1 per pulse		R_1' per pulse	
	Case (i)	Case (ii)	Case (i)′	Case (ii)′
0.1	0.0001	0.004	0.001	0.02
0.2	0.001	0.07	0.008	0.12
0.3	0.005	0.21	0.018	0.28
0.4	0.011	0.34	0.025	0.39
0.5	0.014	0.40	0.028	0.43
0.6	0.016	0.39	0.026	0.40
0.7	0.015	0.33	0.021	0.33
0.8	0.013	0.25	0.016	0.26
0.9	0.010	0.18	0.012	0.18
1.0	0.007	0.13	0.008	0.13

The values of $\Delta\Omega$ and $\Delta p/p$ assumed in Table 1 agree with estimates made by Humphrey [11] for a pion storage ring suitable for operation in conjunction with the Tevatron. One expects that these values could be substantially improved in specially designed storage rings.

Table 2 shows values of the ratio $\rho = R_1/(R_2/3)$ *vs* z for cases (i) and (ii), and of $\rho' = R_1'/(R_2/3)$ for cases (i)′ and (ii)′. The values of ρ were obtained by means of Eq. (A9) of the appendix and those of ρ' by an appropriate modification of Eq. (A9). In Table 2 it is assumed that the length L of the

Table 2 — Values of $\rho = R_1/(R_2/3)$ for cases (i) and (ii), and of $\rho' = R_1'/(R_2/3)$ for cases (i)' and (ii)', assuming that $L = 0.4$ km for cases (i) and (i)', and that $L = 1.0$ km for cases (ii) and (ii)'.

z	ρ		ρ'	
	Case (i)	Case (ii)	Case (i)'	Case (ii)'
0.1	0.0002	0.001	0.004	0.004
0.2	0.005	0.015	0.028	0.028
0.3	0.019	0.048	0.063	0.063
0.4	0.037	0.077	0.089	0.089
0.5	0.051	0.091	0.098	0.098
0.6	0.056	0.089	0.091	0.091
0.7	0.052	0.074	0.076	0.076
0.8	0.044	0.058	0.058	0.058
0.9	0.034	0.042	0.042	0.042
1.0	0.025	0.029	0.029	0.029

decay tunnel to which R_2 corresponds is 0.4 km in cases (i) and (i)', and 1.0 km in cases (ii) and (ii)'. The ratio ρ (respectively, ρ') sefers to unfocused (focused) π^+'s injected into the ring, and to π^+'s with "good" focusing (rather than perfect focusing, hence the use of $R_2/3$) decaying in the pertinent tunnel. Notice that when Eq. (A9) and its alluded modification are valid, $\rho \propto \eta L^{-1}(J\Delta p/p)$ and $\rho' \propto \eta L^{-1}E_0(\Delta p/p)$.

Some comments on the results in Tables 1 and 2 and on implications of these results are in order.

Table 1 illustrates the expected result that focusing of the pions before injection into a ring produces significant increases in the relevant muon rates in the detector only at sufficiently low values of z.

Although the values of ρ and ρ' in Table 2 are small compared to unity, due in particular to the conservative values of $\Delta\Omega$ and $\Delta p/p$ assumed in this table, our calculations predict that under appropriate conditions method (a) is capable of producing muon rates in 10^5-ton detectors (suitably instrumented and shielded) which should be measurable above background, even at thousands of kilometers from the accelerator. (If sunlight is absent or if adequate shielding against it has been provided, the main background source is constituted by cosmic-ray muons.) Consider, for example, a proton accelerator with an $l = 1$ target on which 450 pulses/h of 5×10^{13} protons/pulse are incident, and a 10^5-ton water detector. By suitably scaling results in Table 1, we find for $\Delta p/p = 0.01$ and $\eta = 0.2$: (1) that method (a) would yield $\sim 1/2\ \mu^-$/h (respectively, $\sim 1\ \mu^-$/h) in this detector at $D = 10^3$ km for case (i) (respectively, case (i)') assuming $cp = 160$ GeV; and (2) that this method would yield $\sim 1\ \mu^-$/h in this detector at $D = 3.2\times10^3$ km for cases (ii) and (ii)', assuming $cp = 300$ GeV. These rates would suffice for investigating the occurrence of neutrino oscillation phenomena in neutrino beams transmitted through the earth over such distances.

If a greater value of $\Delta p/p$ of, say, 0.05 is assumed, but the values of the other parameters in Table 2 are unchanged, then the values ρ and ρ' between $\sim$0.3 and $\sim$0.5 can be obtained in the respective cases (ii) and (ii)' for the appropriate range of z values. From this together with previous remarks in this section and other straightforward considerations, one can conclude that the muon production rates obtainable by method (a) at $E_0 = 1$ TeV are suitable for low-data-rate global neutrino communication, provided in particular that storage rings with these larger values of $\Delta p/p$ were available.

Method (a) would thus appear preferable to utilizing a standard decay tube design, if the total circumference of the storage ring were small compared to the length of the decay tunnel used for comparison. Unfortunately, present superconducting technology does not permit one to design rings for fields much in excess of 5 tesla, thus causing the storage ring to be relatively large. The application of curved crystal technology to the bending of high-energy beams could conceivably yield reasonably compact storage rings, since the equivalent magnetic field from this method might correspond to 500 tesla or more.

Methods (b)-(d)

We next proceed to an estimate of neutrino intensities and muon event rates in method (b). Wilson [12] lists the available external muon beams at CERN and at the Tevatron, quoting muon intensities of 10^8 to 10^9/s. The muon spectra peak at energies similar to those of the pions, except for extending further towards lower energies due to π-μ decay occurring close to the backward direction in the CM system. The storage-ring acceptances are quite similar to those of the pions, so that essentially only the intensity ratio of pion *vs* muon beam (10^{12}/s *vs* 10^8 to 10^9/s) matters. We thus arrive at muon event rates caused by $\bar{\nu}_\mu$'s from μ^+-decay in a storage ring which are $\leqslant 10^{-3}$ of the corresponding rates due to ν_μ's from π^+-decay in the ring. Whence we conclude that method (a) is preferable to method (b) for neutrino communication, since neutrino beams of sufficiently high intensity are essential for this purpose. Moreover, method (b) does not have a significant advantage possessed by method (a) for the scientific applications discussed in the next section of this report, since it would not yield monochromatic neutrino beams. However, method (b) does provide a beam of ν_e's having roughly the same flux and spectra as the muon neutrinos. Such relatively intense ν_e beams would be desirable for a study of ν_e interactions and propagation.

Further, method (c) does not appear as promising as method (a) either, at least with presently available external muon beams from meson factories such as LAMPF (Los Alamos Meson Production Facility) or SIN (Swiss Institute for Nuclear Research). The most intense μ^+ source of these seems to be the μE1 beam of SIN [13-16] which, assuming the maximum intensity 100 μA of the proton beam at SIN, furnishes 115-MeV/c muons, peaked within a $\pm 10\%$ interval, from backward-decaying pions* with a total intensity of 1×10^8/s (the LAMPF μ^+ beam, by contrast, consists of 6×10^7/s muons at up to 140 MeV/c. Unfortunately, however, the dimensions of this beam are 6×4 cm^2. Therefore, even if a momentum byte of $\pm 7\%$ were achieved for acceptance [16] into a linear accelerator that subsequently would accelerate the muons up to several hundreds of GeV/c, the large dimensions of this beam would seem to indicate that only perhaps ~0.1% of the beam could be accelerated to that energy,† with further losses upon its subsequent injection into a muon-storage ring. The resulting neutrino-induced muon event rates of far less than 1 event/h appear to eliminate scheme (c) as a practical means for neutrino communication.

Method (d), *i.e.*, the use of an electron accelerator as a muon source, with subsequent acceleration of the muons to higher energies, has elements similar to a muon storage ring proposal of Tinlot and Green [17] and to a particle reinjection proposal discussed by Herrmannsfeldt [18], by which one could recirculate an electron beam through the same (SLAC-type) electron accelerator for further acceleration. Unfortunately, method (d) is impractical for efficient muon production since the emittance of the muon beam obtained here (~30 cm mrad) is much greater than the acceptance of a SLAC-type accelerator (~4×10^{-2} cm mrad), giving a mismatch such that only 2×10^{-6} of the created muons can be reinjected for acceleration to higher energy.

*A muon beam of about four times this intensity may also be made available at SIN (from the forward-decaying pions), with momentum ~200 MeV/c, which is heavily contaminated with pions [16].

†A SLAC-type linear accelerator that accelerates muons from 100 MeV/c to 100 GeV/c can do this over a length of ~18 km; the linac could be curved on itself and the accelerating cavities reused by the particles.

OTHER APPLICATIONS OF NEUTRINO BEAMS FROM PION STORAGE RINGS

In this section, we discuss applications of such beams to the measurement of possible neutrino-oscillation effects on long-distance neutrino propagation through the earth and to improved measurements of neutrino cross sections. The first of these applications is not only of great importance from a basic high-energy physics and astrophysics viewpoint, but as emphasized by the present authors [3] also from the viewpoint of global neutrino communication. The presence of neutrino oscillations could seriously complicate the use of neutrino beams for this purpose, *e.g.*, by producing blind spots in certain directions of neutrino travel through the earth [3].

Muon neutrino beams produced by method (a) have two important properties with respect to the scientific applications. Since such beams arise from the two-body decay Reaction (1a) of essentially monochromatic pions, the neutrinos generated in any given direction have this monochromaticity property. Another relevant property is that the neutrino beam's energy at a given angle can be varied by changing the pion energy at which the momentum byte injected into the ring is taken. We denote these two properties jointly as "tunable monochromaticity."

Machine-produced monochromatic neutrino beams aimed through the earth could be employed as sensitive tools to study neutrino oscillations. In particular, they would be especially valuable for determining whether any oscillation effects which might be observed are caused by pure vacuum oscillations [19], or by oscillations containing a matter-induced component [20]. If they exist, these effects are expected to manifest themselves over distances of $\sim 10^4$ km, *i.e.*, of the order of the earth's diameter. By varying the neutrino beam energy, one could distinguish between vacuum oscillations (which are sensitively dependent on neutrino energy) and matter oscillations (which are independent of this energy). Moreover, one could ascertain the presence of a matter-induced component in the vacuum oscillations, since such a component is expected to modify the simple momentum dependence of pure vacuum oscillations (with an oscillation length directly proportional to the momentum).

It is well known that monochromatic neutrino beams would offer important advantages for the measurement of neutrino cross sections. For this reason, schemes to produce "monochromatic" neutrino beams were proposed previously [21]. A "dichromatic" neutrino beam was set up at Fermilab [22], capable of producing a neutrino beam with a peak of neutrinos from pion decay at $E_\nu \sim 55$ GeV of width $\Delta E_\nu / \langle E_\nu \rangle \sim 0.6$ and a second peak of neutrinos from kaon decay at ~ 150 GeV, with about the same value of $\Delta E_\nu / \langle E_\nu \rangle$ [23]. The width of the spectrum of neutrinos produced by our proposed methods (a) would be comparable to the momentum byte of the pions accepted by the storage ring, say $\Delta p/p = 0.01$. Furthermore, we estimate that the decay of high-energy pions in a storage ring could be arranged to yield muon count rates several times larger than those produced by monochromatic pion decay in a conventional decay tunnel, having a length equal to the straight section of the ring.

The usefulness of such a neutrino beam for cross-sectional measurements would be quite considerable, especially for neutral-current events where the outgoing lepton is also a neutrino. With a spectrum of incident neutrinos, the final state does not provide enough information to reconstruct the event. But if the source direction and the incident neutrino energy are known, the event can be reconstructed completely and its signature is specific.

CONCLUSIONS

In the present study, we have proposed and analyzed four methods for generating high-energy neutrino beams in storage rings, concluding that of these methods, pion decay in appropriately shaped storage rings offers the best prospects (relatively speaking) with respect to the envisioned scientific and technological applications.

The direction of a neutrino beam generated in a storage ring can be varied to some degree by using movable straight sections in the ring. The fact that sufficiently narrow pion momentum bytes, centered about momenta which can be selected from a wide range, can be injected into such a ring leads to a tunable monochromaticity of the neutrino beams generated by pion storage rings. To effectively use such rings for neutrino communication over global distances, it will be necessary to design them with a sufficiently large $\Delta p/p$ acceptance, say of 5%. The use of a storage ring equipped with movable straight sections for this application, in place of a multiplicity of long decay tunnels, would render the mentioned application practicable, provided a suitably compact storage ring can be constructed. At this time, this may appear difficult due to the limitations of present-day superconducting technology, and perhaps also because of economic considerations.

As to scientific applications of the monochromatic neutrino beams generated by pion decay in storage rings, we have pointed out that they could be used for performing neutrino oscillation experiments over distances of thousands of kilometers through the earth, and that by means of such beams it would be possible to distinguish effects due to vacuum oscillations from those due to matter-induced oscillations. These beams would also permit a more complete reconstruction of (especially) neutral-current neutrino reactions in (short-distance) accelerator experiments than is possible at present, hence greatly improving the interpretation of such experiments. A factor of up to ~ 10 may be gained in producing a monochromatic neutrino beam by a storage ring, rather than by a conventional decay tunnel, but this increase in flux may perhaps not be sufficient to justify the cost of the storage ring. The use of a storage ring for muons, methods (b) - (d), would provide a relatively enhanced source of electron neutrinos from muon decay, and may be the only means for providing a sufficient flux for terrestrial ν_e experiments. Methods (b) - (d) would, however, not provide a sufficiently intense neutrino beam for use in long-range neutrino communications systems.

ACKNOWLEDGMENTS

We thank L. Sulak, K. Lande, A. Fainberg, S. Penner, R. Arnold, and S. Lobowitz for helpful discussions.

REFERENCES

1. A.W. Sáenz, H. Überall, F.J. Kelly, D.W. Padgett, and N. Seeman, *Science* **198**, 295 (1977).

2. A.W. Sáenz, H. Überall, F.J. Kelly, D.W. Padgett, and N. Seeman, in *Neutrinos-78,* Proc. Int. Conf. Neutrino Phys. and Astrophys., West Lafayette, Indiana, 1978, E. C. Fowler, ed. (Purdue University, 1978), p. C168; *Bull. Am. Phys. Soc.* **23**, 545 (1978).

3. F.J. Kelly, A.W. Sáenz, and H. Überall, in *Long-Distance Neutrino Detection-1978* (C.L. Cowan, Memorial Symp., Catholic University), AIP Conference Proceedings No. 52, A.W. Sáenz and H. Überall, eds. (AIP, New York, 1979), p. 113.

4. H. Überall, F.J. Kelly, and A.W. Sáenz, "Neutrino Beams: A New Concept in Telecommunications," *Proc. Washington Acad. Sci* **69**, 48 (1980).

5. R.R. Wilson, *Rev. Mod. Phys.* **51**, 259 (1979).

6. See, *e.g.*, B. Cox and C.T. Murphy, in the *1976 Summer Study*, Utilization of the Energy Doubler/Saver, J. Lach, ed. (Fermilab, Batavia, Ill.), Vol. 2, p. 261.

7. A. Skuja, *ibid.*, Vol. 2, p. 159.

8. C.L. Wang, *Phys. Rev. D* 7, 2609 (1973); *Phys. Rev. D* **10**, 3876 (1974).

9. C. Baltay, in *Muon Physics*, Vol. II, V.W. Hughes and C.S. Wu, eds. (Academic, New York, 1975), p. 304, Eq. (54).

10. R.J. Stefanski and H.B. White, "Neutrino Flux Distributions," Fermilab Report FN-292, May 10, 1976.

11. J.W. Humphrey, in *1976 Summer Study* [6], Vol. 1, p. 433.

12. R. Wilson, in *Proc. 1977 Summer Workshop "Isabelle,"* Brookhaven National Laboratory Report BNL 50721, p. 421.

13. C. Tschalär, "Muon Spectra from Pion Production Targets," Los Alamos Laboratory Informal Report LA-7222-MS, June 1978.

14. "Medium-Energy Physics Program," May 1 - July 31, 1978 and Feb. 1 - April 30, 1978, Los Alamos Scientific Laboratory Progress Reports LA-7650-PR and LA-7607-PR.

15. SIN Annual Report 1978, Swiss Institute for Nuclear Research, Villigen, Switzerland, pp. B7-B11; see also SIN Newsletter No. 6, February 1976, pp. 4-6.

16. C. Petitjean, "The Superconducting Muon Channel Facility of SIN," paper submitted to the Muon Physics Conference, Fort Collins, Col., Sept. 6-10, 1971 (updated May 1974).

17. J. Tinlot and D. Green, *IEEE Trans. Nucl. Sci.* **12**, 470 (1965).

18. B. Herrmannsfeldt, "The SLAC Recirculating Linear Accelerator," SLAC-PUB-1205 (A), March 1973.

19. B. Pontecorvo, *Soviet Phys. JETP* **26**, 984 (1968).

20. L. Wolfenstein, *Phys. Rev. D* **17**, 2369 (1978). See also L. Wolfenstein, in *Long-Distance Neutrino Detection-1978* [3], p. 108.

21. V.Z. Peterson and D. Keefe, *Proc. Conf. Neutrino Physics*, 1965, CERN Report CERN-65-32, p. 241.

22. See, *e.g.*, P. Limon *et al.*, *Nucl. Instr. Methods* **116**, 317-321 (1974). See also C. Baltay *et al.*, in the *1976 Summer Study* [6], Vol. 2, p. 43; and B. Cox and C. T. Murphy [6].

23. B.C. Barish *et al.*, *Proc. Int. Neutrino Conf. Aachen*, 1976, H. Faissner, H. Reither, and P. Zerwas, eds. (Vieweg, Braunschweig, 1977), p. 22.

Appendix

FORMULAS FOR NEUTRINO-INDUCED MUON RATES AT LARGE DISTANCES FROM THE ACCELERATOR

In this appendix, we collect some formulas for the muon rates produced by a muon-neutrino beam in a detector situated at such a large distance from the beam's source that the latter can be considered as a point-source. We discuss the cases in which the beam is produced by pion decay in a storage ring and by the decay of perfectly focused pions in the decay tunnel of an accelerator. In both cases, we assume that the pions are generated by pulses of protons of hundreds of GeV's colliding with the nuclei of the target. We make the usual simplifying assumption that the absorptive interaction length of the pions in the target equals that of the parent protons.

According to the Stefanski-White model [A1], the pion spectrum produced by proton-nucleus collisions is given in the laboratory frame by

$$d^2N/dpd(\cos\theta) = ABC^2e^{-Bp/E_0-Cp\sin\theta} \tag{A1}$$

per interacting proton, where p is the pion momentum in GeV/c, E_0 is the primary proton energy in GeV, and θ is the angle between the incident proton and the produced pion. We define

$$C = C(p/E_0) = C_0 - 1.43e^{-p/E_0-2p^2/3E_0^2} \tag{A2}$$

and

$$\begin{aligned} A = 5,\ B = 8,\ C_0 = 6 \text{ for } \pi^+, \\ A = 4,\ B = 10.25,\ C_0 = 6 \text{ for } \pi^-. \end{aligned} \tag{A3}$$

Let a momentum byte Δp of π^+'s be taken from the pion spectrum generated by an accelerator pulse of N_p protons of energy E_0 which is incident on the target considered, and let this byte be injected into a storage ring with a straight section of efficiency η. We make the following assumptions. We assume that the amplitudes of the transverse oscillations of the pion beam in the section are made to be so small, by appropriate focusing, that all the pions in the section can be considered as traveling parallel to its axis, as far as the calculation of muon intensities at distant detectors is concerned. We suppose that the straight section points accurately toward a water Cerenkov detector situated at a distance D from the accelerator, and which subtends such a small angle with the detector that the flux of ν_μ's reaching the detector is approximately the same as the ν_μ flux produced by forward π^+ decay. Moreover, we assume now that the pions injected into the ring are *unfocused*; we will consider the other extreme case when they are perfectly focused before injection later on in this appendix. Under these circumstances, the number R_1 of μ^-'s per pulse produced in the detector *via* Reaction (2a) by the beam of ν_μ's emerging from the straight section is given by

$$R_1 = \frac{1}{\pi}\eta le^{-l}N_pN_dV_d\,(\kappa_\nu/m^2c^3)\,(1-m'^2/m^2)(dN/dp)\,\Delta\Omega\,(\Delta p/p)\,p^4D^{-2}, \tag{A4}$$

where l is the length of the accelerator's target in units of the proton-nucleus absorptive interaction length at energy E_0, N_d is the nucleon number-density of the detector (6.02×10^{23}), V_d is the volume of the detector (volume where these muon events are being surveyed), $\alpha_\nu = 0.61 \times 10^{-38}$ cm^2/GeV, m and m' are the $\pi^\pm$ and $\mu^\pm$ masses, respectively, p is the momentum at which the byte Δp is taken, and $(dN/dp)\,\Delta\Omega$ is the integral

$$(dN/dp)\,\Delta\Omega = \int_0^{\theta_0} (d^2N/dpd(\cos\theta))\sin\theta\, d\theta, \tag{A5}$$

evaluated at the latter momentum value, with $\Delta\Omega = \pi\theta_0^2$. We are considering here the idealized situation in which those, and only those, pions in the byte Δp which emerge from the target (pictured crudely as a "point source") within a cone of semiangle θ_0 whose axis is parallel to the momentum vector of the protons at the target are accepted by the ring.

Equation (A4) was derived by using, in particular, simple arguments of relativistic kinematics and the linear dependence $\sigma_\nu = \kappa_\nu E_\nu$ of the total cross section σ_ν of Reaction (2a) on neutrino energy [A2] in the energy region of interest.

For the Stefanski-White spectrum (A1), the integral (A5) can be performed in closed form in the small-angle approximation ($\sin\theta \approx \theta$), which is valid in the high-energy region relevant to this discussion. We find from Eqs. (A1) to (A5) that

$$\begin{aligned} R_1 = {} & 3.770 \times 10^4 \eta^{-1} Vd(10^6\mathrm{m}^3) \\ & \times N_p\,(10^{13}\ \text{protons})(E_0(\mathrm{TeV}))^3(D(10^3\ \mathrm{km}))^{-2} f(z,\theta_0 E_0)(\Delta p/p), \end{aligned} \tag{A6}$$

where

$$f(z,\theta_0,E_0) = z^4 e^{-Bz}(1 - e^{-\alpha} - \alpha e^{-\alpha}), \tag{A7}$$

with $z = cp/E_0$ and

$$\alpha = \alpha(z,\theta_0,E_0) = \theta_0 E_0 C(z). \tag{A8}$$

Let all the previous assumptions be made, except that instead of supposing that unfocused pions are injected into the ring, the π^+'s produced by the pulse of N_p protons are assumed to be perfectly focused, so that all those in the above momentum byte Δp are accepted by the ring. The corresponding number of ν_μ's per pulse in the detector is then given by Eq. (A4), but with $f(z,\theta_0,E)$ replaced by $z^4 e^{-Bz}$.

Consider now the situation in which the π^+'s produced by a pulse of protons are perfectly focused and all of them are then directed into a decay tube of length L. Again neglecting any pion-beam-divergence effects, the number R_2 of μ^-'s per pulse produced in the detector, *via* Reaction (2a), by the decay of these pions is related to R_1 by

$$\begin{aligned} R_1/R_2 = {} & 1.421 \times 10^4 \eta\, E_0(\mathrm{TeV})(L\,(\mathrm{km}))^{-1} \\ & \times f(z,\theta_0,E_0)(\Delta p/p) \end{aligned} \tag{A9}$$

when Eqs. (A1) to (A3) obtain, provided that R_1 and R_2 in Eq. (A9) refer to the same number of protons per pulse interacting with the same target, and to the same detector situated at the same place. Moreover, the previously stated forward-decay condition is supposed to be satisfied by R_1 and R_2.

Equation (A10) follows from Eq. (A7) and an equation for R_2 obtainable by arguments similar to those employed in deriving Eq. (A7).

Similar formulas can be written for the μ^+-production rates in a distant detector induced *via* the reaction

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons} \tag{A10}$$

by a beam of $\bar{\nu}_\mu$'s generated by the decay

$$\pi^- \rightarrow \bar{\nu}_\mu + \mu^+ \tag{A11}$$

of π^-'s confined in a storage ring or traveling through a conventional decay tunnel.

REFERENCES

A1. R.J. Stefanski and H.B. White, "Neutrino Flux Distributions," Fermilab Report FN-292, May 10, 1976.

A2. B.C. Barish *et al.*, *Phys. Rev. Lett.* **39**, 1595 (1977).